THE RESISTANCE OF METALS UNDER PRESSURE

By P. W. Bridgman

JEFFERSON PHYSICAL LABORATORY, HARVARD UNIVERSITY

Communicated by E. H. Hall, November 27, 1916

In this note are summarized many of the most important results of an extended series of measurements on the resistance of metals under hydrostatic pressure. A more detailed account of the experiments has been offered for publication in the *Proceedings of the American Academy of Arts and Sciences.* The pressure range of this work is from 0 to 12,000 kg., and the temperature range from 0° to 100°C. The most extensive previous measurements have been made by Lisell and Beckman,[1] who made all their measurements at 0° over a pressure range of 3,000 kg.

This investigation includes 22 metals, embracing nearly all the common metals obtainable in the form of wire. Special precautions were taken in most cases to insure the greatest possible purity; the temperature coefficient of resistance at atmospheric pressure affords an indication of the probable purity. Of the metals above, Sn, Cd, and Zn were Kahlbaum's 'K' grade, Tl and Bi were prepared by electrolysis and were of high purity, Pb, Ag, Au, Cu, Fe, and Pt were of exceptional purity, and the others are probably not better than of high commercial purity except Al, which was much better than ordinary.

The results are summarized in the table. Two kinds of pressure coefficient are listed: 'instantaneous coefficient' and 'average coefficient'. The 'instantaneous coefficient' is the value of the derivative $\frac{1}{w}\left(\frac{\partial w}{\partial p}\right)_t$, where w is the observed resistance at the pressure and temperature in question. The 'average coefficient' between 0 and 12,000 kg. is the total change of resistance between 0 and 12,000 kg. divided by 12,000 and by the resistance at atmospheric pressure at the temperature in question.

The effect of pressure is to decrease the resistance of all metals except Bi and Sb, the resistance of which suffers a comparatively large increase. The anomalous behavior of Bi was known before, but that of Sb is new. The Sb was used in the form of extruded wires. The magnitude of the effect for normal metals varies from 12% to 0.8% for 10,000 kg., but Te forms a notable exception.

It is apparent from the table that the relative change of pressure coefficient with temperature is much less than the relative change of

resistance itself; the direction of change may be either an increase or a decrease. Another statement of this fact is that the temperature coefficient changes very little with pressure; this is shown in the second and the third columns of the table. This is perhaps surprising when it is remembered that the pressures used here are in many cases great enough to compress the metal to considerably less than its volume at O°Abs. at atmospheric pressure. The instantaneous coefficient de-

TABLE

METAL	AVERAGE TEMPERATURE COEFFICIENT 0 TO 100°		PRESSURE COEFFICIENTS					
			Instantaneous coefficient at 0°		Instantaneous coefficient at 100°		Average coefficient 0 to 12,000 kg.	
	At 0 kg.	At 12,000 kg.	At 0 kg.	At 12,000 kg.	At 0 kg.	At 12,000 kg.	At 0°	At 100°
In	+.00406	+.00383	$-.0_{4}1226$	$-.0_{4}1016$	$-.0_{4}1510$[3]	$-.0_{4}1072$[3]	$-.0_{4}1021$	$-0._{4}1131$[3]
Sn	447	441	$_{4}1044$	$_{5}936$	$_{4}1062$	$_{5}973$	$_{5}920$	$_{5}951$
Tl	517	499	$_{4}1319$	$_{4}1180$	$_{4}1456$	$_{4}1200$	$_{4}1151$	$_{4}1226$
Cd	424	418	$_{4}1063$	$_{5}837$	$_{4}1106$	$_{5}887$	$_{5}894$	$_{5}927$
Pb	421	412	$_{4}1442$	$_{4}1220$	$_{4}1483$	$_{4}1237$	$_{4}1212$	$_{4}1253$
Zn	416	420	$_{5}540$	$_{5}425$	$_{5}524$	$_{5}407$	$_{5}4700$	$_{5}4544$
Al	434	435	$_{5}416$	$_{5}365$	$_{5}397$	$_{5}373$	$_{5}3815$	$_{5}3766$
Ag	4074	4069	$_{5}358$	$_{5}321$	$_{5}355$	$_{5}331$	$_{5}3332$	$_{5}3362$
Au	3968	3964	$_{5}312$	$_{5}286$	$_{5}304$	$_{5}292$	$_{5}2872$	$_{5}2918$
Cu	4293	4303	$_{5}201$	$_{5}179$	$_{5}184$	$_{5}175$	$_{5}1832$	$_{5}1770$
Ni	4873	4855	$_{5}158$	$_{5}142$	$_{5}163$	$_{5}156$	$_{5}1473$	$_{5}1575$
Co	3657	3676	$_{6}941$	$_{6}814$	$_{6}755$	$_{6}704$	$_{6}873$	$_{6}726$
Fe	6206	6184	$_{5}241$	$_{5}218$	$_{5}247$	$_{5}230$	$_{5}2262$	$_{5}2353$
Pd	3178	3185	$_{5}198$	$_{5}190$	$_{5}189$	$_{5}187$	$_{5}1895$	$_{5}1863$
Pt	3868	3873	$_{5}1975$	$_{5}181$	$_{5}190$	$_{5}182$	$_{5}1870$	$_{5}1838$
Mo	4336	4340	$_{5}133$	$_{5}126$	$_{5}130$	$_{5}125$	$_{5}1286$	$_{5}1265$
Ta	2973	2967	$_{5}149$	$_{5}139$	$_{5}153$	$_{5}147$	$_{5}1430$	1486
W	3219	3216	$_{5}128$	$_{5}121$	$_{5}130$	$_{5}123$	$_{5}1234$	$_{5}1258$
Mg	390[1]		$0_{5}55$				$0_{5}55$	
Sb	473	403	$+\ 0_{4}1220$	$+\ _{4}1064$	$+\ _{5}768$	$+\ _{5}723$	$+\ _{4}1220$	$+\ _{5}768$
Bi	438	395	$+\ 0_{4}154$	$+\ _{4}213$	$+\ _{4}152$[4]	$+\ _{4}1895$[4]	$+\ _{4}2228$	$+\ _{4}1980$[4]
Te	$-.0063$[2]		$-.0_{3}129$					

[1] 0° to 20°, [2] 0° to 24°, [3] extrapolated from 50°, [4] extrapolated from 75°.

creases with rising pressure, as is natural, but it is at first sight strange that the percentage decrease is in nearly all cases less at the higher temperatures.

The numerical results of the above table are not in particularly good agreement with the previous results of Lisell and Beckman.[1] Suggestions as to the reasons for the discrepancies may be found in the detailed paper. Beckman has made extended application of his results to a theory of the pressure effect recently put forward by Grüneisen,[2] and

has come to the conclusion that Grüneisen's theory can not be more than a first approximation. This conclusion will not be altered by using the values of the table above instead of those of Beckman.

The theory of Grüneisen is incomplete in the sense that it gives the pressure coefficient of resistance in terms of the temperature coefficient as well as several thermodynamic constants. I hope to show at some length elsewhere that both the temperature and the pressure coefficient of resistance may be calculated with better agreement than by Grüneisen's formula by putting the proportional change of resistance in any direction equal to twice the proportional change of average amplitude of atomic vibration. This is capable of theoretical explanation on the ground that when the atoms are at rest the electrons pass freely from atom to atom, but when the separation of the atoms by haphazard heat agitation becomes too great, the electrons encounter difficulty in jumping from atom to atom.

The expenses of this investigation were in large part met by generous appropriations from the Bache Fund of the National Academy of Sciences, and from the Rumford Fund of the American Academy of Arts and Sciences.

[1] Lisell, E., Inaug. Dis., Upsala, 1902; and Beckman, B., Inaug. Dis., Upsala, 1911; *Ark. Mat. Astr. Fys.*, 7, 1912, No. 42 (1–18); *Ann. Physik., Leipzig*, **46**, 1915, (481–502) and (931–941); *Physik. Zs., Leipzig*, **16**, 1915, (59–63).

[2] Grüneisen, E., *Berlin, Verh. D. physik. Ges.*, **15**, 1913, (186–200).

THE RATE OF DISCHARGE OF CENTRAL NEURONES

By Alexander Forbes and W. C. Rappleye

LABORATORY OF PHYSIOLOGY, HARVARD MEDICAL SCHOOL

Communicated by W. B. Cannon, November 27, 1916

The frequency of nerve impulses discharged from the central nervous system in voluntary and reflex contraction of the skeletal muscles presents a problem concerning which great difference of opinion is found among investigators. Piper, studying the electrical disturbance with a string galvanometer, has shown that in human muscles a fairly regular series of action currents with a rhythm of about 50 per second accompanies voluntary contraction. He inferred from this that the central nervous system sends to the muscle 50 impulses per second.

Buchanan, chiefly on the basis of experiments on frogs, reached the conclusion that the observed rhythm is not that of the motor nerve impulses but is dependent on the condition of the muscle itself.